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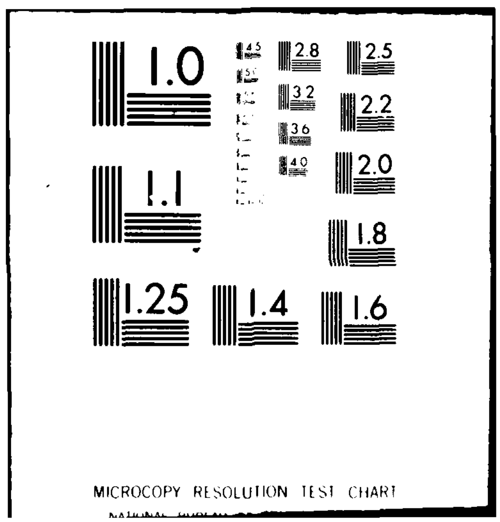
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FOREIGN TECHNOLOGY DIVISION

PULSE LASER RANGING SYSTEMS

by

Zdenko Adelsberger

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PULSE LASER RANGING SYSTEMS

Zdenko Adelsberger
Captain, Dipl. Eng.

The principle of operations

Laser ranging represents the first practical application of lasers for military purposes. The first pulse laser for ranging was made already in 1961, immediately after the first practical laser demonstration. This measuring device was constructed in the USA and was referred to as MARK I COLIDAR (Coherent Light Detecting and Ranging). In relation to the present day development of these devices it was a relatively primitive device. However, the principle of operation (figure 1) has remained the same.

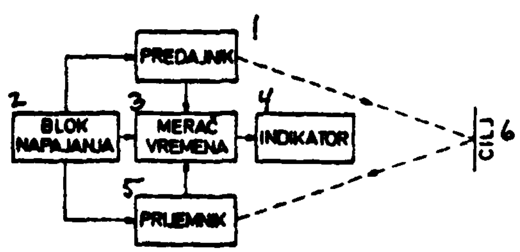

Figure 1. Schematic diagram of a pulsing laser principle for distance determinations.
Key: 1 - emitter; 2 - generating block; 3 - timing device; 4 - indicator; 5 - receiver; 6 - target.

As observed in fig. 1 the basic parts of this system are the emitter, the receiver, the timer, the indicator, and the generating block. The principle of measurement of the distance is reduced to the measurement of the time required for the pulse to travel from the moment it is generated at the emitter to the

target and back to the receiver.

Until the advent of laser devices, the distance was practically measured using the, so called, optical rangers where the principle of distance determination is reduced to calculation of the length of one side of the triangle where the base and the angle between them are known. The accuracy of this type of measurement is determined by the width of the base. The error is decreased by the increase of the base. In addition, an essential part of the error is contributed by the man (operator). With optical rangers the error is increased with the increase of the measuring distance. In contrast, with the laser type rangers, the error of the measurement is determined in advance for the requirements of the user (for the military requirements it is usually from ± 5 to ± 10 m) and does not change with the measuring distance. In addition, the possibility of an operator error in the process of measurement can be practically excluded.

Figure 2 shows the values for the average error in distance measurements for optical rangers with the various bases (B), and also for laser rangers.

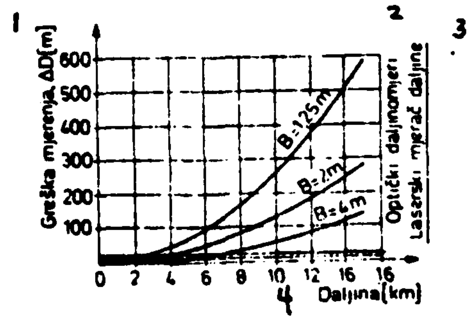

Figure 2. The average ranging error for optical and laser rangefinders

Key 1 - measuring error ΔD(m); 2 - optical rangefinder; 3 - laser rangefinder; 4 - distance (km)

Besides the pulse lasers, continuous type lasers (CW) are also used for ranging. These are the, so called, phase rangefinders where the laser signal is amplitudinally modulated with

a radio frequency and the reference and the reflected signals are compared in the receiver. The distance of the target from which the signal was reflected can be obtained from the phase difference. By comparing the pulse and the phase type laser rangefinders one can conclude that the phase type is more accurate but also more complicated. The pulse laser rangefinders have found great applications in all types of modern armies because of their relative simplicity, longer reach (higher emission power) and small measurement error.

In comparing the optical and the laser rangefinders, the optical device has only one advantage, its measuring action is not self-exposed. In other words, it is relatively simple to determine at the target, whether a laser rangefinder is in operation. This is the consequence of any active system of determination in comparison with the optical systems which are passive.

Because of its characteristics, each component of pulse laser rangefinders will be discussed separately.

The emitter

Laser is the basic element of the emitter. It also contains additional electronic subsystems which assure proper operation of the laser as a part of the whole device and an optical system for collimation of the emitted laser pulse. The laser is the most interesting part of the emitter and thus a little more will be said about it.

Today there are many kinds and types of lasers which differ in their state of aggregation of their active matter, wavelength of their emission, degree of monochromatism, yield coefficient power and energy of radiation, and a long series of other characteristics.

TABLE

1 Tip lasera	2 Režim rada	3 Valna dužina [μm]	4 Snaga zračenja [W]	5 Energija zračenja [J]	6 Frekv. pojas [Hz]	7 Trajanje impulsa [s]	8 Repetic. frekv. impulsa [Hz]	9 Diverg. snopa [mrad]	η [%]
He-Ne	CW	0,633	0,05	-	2	—	—	0,6—1,5	0,2
CO_2	CW	10,6	$6 \cdot 10^4$	—	50	—	—	3	20
CO_2	Impulsni 12	10,6	10^9	2000	—	$20 \cdot 10^{-6}$	100	—	30
Ar	CW	0,514	5	—	80	—	—	—	0,1
Nd : staklo 10	Impulsni 12	1,06	10^9	30—80	$3 \cdot 10^{11}$	$30 \cdot 10^{-9}$	$3 \cdot 10^{-4}$	6—7,5	0,1
Nd : YAG	Impulsni	1,06	—	0,02	$12 \cdot 10^{11}$	$(10—25) \cdot 10^{-9}$	100	6—7,5	0,1
GaAs	Impulsni	0,9	—	$2 \cdot 10^{-7}$	$2 \cdot 10^{13}$	$30 \cdot 10^{-9}$	100	3	4—10
Rubin 11	Impulsni	0,694	—	7	$9 \cdot 10^{16}$	$(5—30) \cdot 10^{-9}$	0,3	6	0,01

Key: 1 - laser type; 2 - type of operation; 3 - wavelength (μm); 4 - radiation power (W); 5 - radiation energy (J); 6 - frequency band (Hz); 7 - pulse duration; 8 - pulse repetition frequency (Hz); 9 - beam diverg. (mrad); 10 - glass; 11 - ruby; 12 - pulse.

Continuous lasers, with solid active matter, can have radiation power of one hundred watts to one kilowatt. However, in a pulse system, the power may reach a value of 10^9-10^{12} W for the pulse duration of 3 to 10 ns. Frequency of pulse repetition of laser radiation is limited by thermic parameters of the system. A comparison of solid and gaseous lasers shows that the gaseous lasers operate on a significantly narrower wavelength and have a significantly greater radiation energy (up to 2 kJ). It can also be observed in the table that there is considerable variation in beam divergence for various types of lasers. In order to reduce divergence of the laser beam, telescopic objectives are used. The larger the objective diameter the smaller the divergence.

For long distances in the shortwave IF and visible spectra, most often used are rubies, Nd: YAG (Yttrium aluminum garnet) and Nd: glass lasers, operating on a system of Q-modulations. The reason for this is that with this type of lasers one can obtain high emission energies in a very simple way. Q-modulation is obtained by using Q-circuit breakers. In pulse laser rangefinders two types of Q-breakers are used;

a) the rotating reflector (usually a prism) and b) pockels cell. In the first type of the Q-breakers, the optical resonator is made in such a way that it has on one side a one way mirror and on the other side a prism attached to the motor shaft. The laser pulse is generated only when the mirror and the reflecting side of the prism form a resonator. Duration of the pulse formed in this manner depends upon the speed of rotation of the prism. The Q-circuit breaker, using the Pockels cell, is based on the so called Pockels effect principle which appears in crystalline bodies with piezo-properties. At the present, Pockels cells of potassium phosphate (KDP) and ammonium phosphate (ADP) are used most often.

The receiver

In a laser rangefinder the receiver consists of receiving optics, a photodetector, and electronic components such as an amplifier and a level detector. A block diagram of an optical receiver is shown in figure 3. As shown in the figure, there are two methods of detection of laser pulses: direct and heterodyne detection. In direct detection of laser pulses the signal reflected from the target is directed to the sensor surface of a photodetector where output causes a change in current or voltage as a function of the signal intensity. In heterodyne detection two laser signals are mixed at the sensor surface of the photodetector. One is reflected from the target and the other is

obtained from a local laser (oscillator). The photodetector output causes a current which has a frequency $f = \check{v}_L - \check{v}_s$.

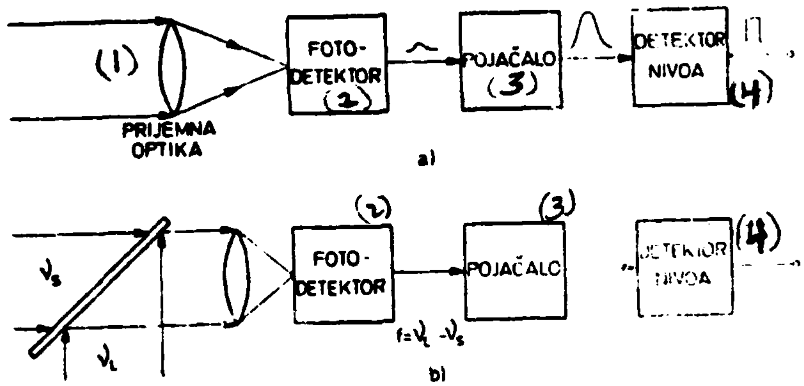

Figure 3. Block diagram of the principle of receiving laser signals a - direct detection; b - heterodyne detection.

Key: 1 - receiving optics; 2 - photodetector; 3 - amplifier; 4 - level detector.

The advantage of a receiver with direct detection is its simplicity and reliability of operation while a heterodyne receiver is more sensitive and gives a higher signal to noise (S/N) ratio).

For photodetectors, the most often used are the photo-multiplying tubes and the PIN and lavine (avalanche) photodiodes. When the transmitters use lasers with wavelength exceeding 1.1 μm other types of photodetectors are also used.

When receiving a laser signal the receiver carries out a space, time and spectral filtration. Space filtration is done by selection of the field of view for the receiver. Strong noise effects which interfere with detection of a useful signal can be significantly eliminated by reduction of the field of view. However, a too small viewing field can significantly complicate the practical use of the system. Figure 4 shows the relationship

between the viewing field of the receiver and the beam divergence of the laser emitter.

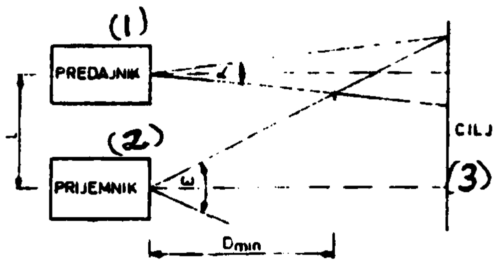

Figure 4. Relationship between the field of view of the receiver (ω) and divergence of the laser beam (α)
Key: 1 - transmitter; 2 - receiver; 3 - target.

Spectral filtration is done using special filters which let through to the surface of the photodetector sensor only the radiation of the wavelength used by the laser emitter. In this way the effect of external noise is also significantly reduced.

For "time filtration", special systems are used to control work of the receivers so that they work only during the period when the reflected signal from the target is to be detected. Special care should be taken that the receiver is turned off until the emitter's pulse passes the distance of D_{min} = 100-200 m where there is a strong effect of laser rays reflected from various small particles in the atmosphere (backscatter). This effect can also be significantly reduced by the very geometry of the equipment (see figure 4). In this case, the viewing field of the receiver and the laser beam should not overlap at the distance D_{min}.

The surface of the target - which could be regarded as a reflector - also has an affect on the range i.e. on the requirements for the sensitivity of the receiver. Each reflector is characterized by the relationship between the effective area of dispersion and the magnitude of the space angle in which the

reflected rays propagate [4]. Thus, for example, for some targets the relationship is given as follows:

$$\frac{A}{\Omega} = \begin{cases} \frac{2}{3} r^2 & \text{for a spherical diffusing reflector of radius } r, \\ \frac{1}{4} r^4 & \text{for a spherical mirror of radius } r, \\ \frac{A}{\pi} & \text{for a diffuse plate of area } A \text{ placed perpendicularly to the laser beam.} \end{cases}$$

When angle ϕ between the normal to the diffusing plate and the direction of the laser beam is equal to zero the effective area is maximized. The value of the effective area is reduced when the angle ϕ is increased. The relative value of the effective area of the target (EPC) as a function of the angle ϕ is shown in fig. 5.

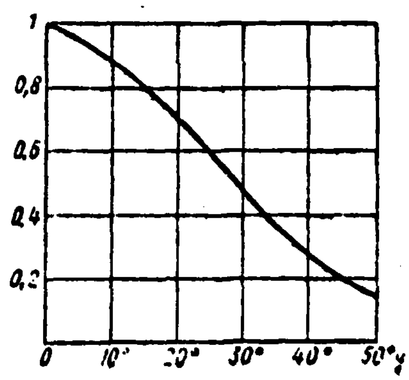

Figure 5. Relative value of the effective area of the target as a function of radiation direction.

The maximum area that can be used by a pulse laser rangefinder is determined by the energy of the receiving signal (reflected from the target). The basic equation for the calculation of the value of the receiving energy is equivalent to the equation for the radar range as follows:

$$E_p = \frac{E_t}{\Omega_t} \cdot \frac{A_t}{D^2} \cdot \frac{\rho}{\Omega_t} \cdot \frac{A_p}{D^2} \cdot \tau^{2D} \qquad (1)$$

where:

E_p = received energy

Ω_e = divergence of the laser beam

A_c = target area

D = measuring range

ρ = target reflection coefficient

Ω_o = space angle of radiation reflected from the target

A_p = area of the receiver opening (objective)

τ = atmospheric transmission coefficient.

Because there are essential differences between the radiation characteristics of classical radars and the laser emitters, and this relation can be presented in a somewhat simplified manner. We must, however, distinguish between these two cases. In the first case, it is assumed that the target is a diffusing reflector having an area equal to or larger than the cross section of the laser beam at the target point. In this case the receiving energy may be calculated according to the equation:

$$E_p = E_e \cdot \rho \cdot \tau^{2D} \cdot \frac{d_o^2}{4D^2} \cdot \tau_1 \cdot \tau_2 \cdot \cos \varphi \qquad (1a)$$

where:

d_o = diameter of the optical receiver

τ_1 and τ_2 = coefficients of transmission of the emitting and receiving optics, respectively,

φ = angle between the laser beam and the normal to the target surface.

In the second case it is also assumed that the target is a diffusing reflector, but it has an area considerably smaller than the cross section of the beam at the target. In this case, the receiving energy can be found by the following relation:

$$E_p = E_e \cdot \rho \cdot \tau^{2D} \cdot \frac{d_0^2 \cdot A_e}{\pi \cdot D^4 \cdot \Omega_0} \cdot \tau_1 \cdot \tau_2 \cdot \cos\varphi \qquad (1b)$$

The quality of the receiver, and the complete system, is defined, among other things, by the minimum energy required by the photodetector as well as by formation of false signals in the receiver itself. These factors are affected by external as well as, by internal noise sources. The most significant external noise is atmospheric - ambient (phonon) and laser photon noise. The internal noise is mainly due to the photodetector and the thermal (Johnson) noise of the photodetector load resistor.

The total S/N for the photodetector output is given by the relation:

$$\frac{S}{N} = \frac{i_s^2}{2eB(i_T + i_s + i_r) + \frac{kTB}{R}} \qquad (2)$$

where:

i_s, i_T, i_r - signal current, dark current and photodetector current, respectively,

e - electron charge,

B - frequency band of the photodetector amplifier,

k - Boltzman constant,

T - absolute temperature

R - load resistor of the photodetector

In order to give proper response, every type of photodetector must become excited by a minimum number of photons of incidental radiation. That minimum number of photons is given by the relation:

$$n_r = \left(\frac{S}{N}\right) \cdot \frac{I_t \cdot t_i}{Me\eta} \qquad (3)$$

where:

I_t - RMS - value for effective noise at the input to the video amplifier of the photodetector,
t_i - input pulse duration,
M - photodetector multiplication factor,
e - electron charge
η - quantum efficiency of the photodetector.

In the case when the area of the target is equal to the cross section of the beam the maximum range for an actual rangefinder can be calculated using equation (3) and, for example, equation (1a). This maximum range value is:

$$D^2 = \frac{E_L}{4 h \nu n_t} \cdot \tau_1 \cdot \tau_2 \cdot d_0^2 \cdot \rho \cdot \tau^{2D} \cos\varphi \qquad (4)$$

For a weak signal the probability of detection of a number (n) of photons (where the threshold photon number is (n_t), is:

$$p_s = p(n \geqslant n_t) = \sum_{n=n_t}^{\infty} e^{-n_s} \frac{n_s^n}{n!} \qquad (5)$$

where:

n_s - the average number of signal photons during the pulse.

The probability of appearance of a false signal is given by:

$$p_L = p(n \geqslant n_t) = \sum_{n=n_t}^{\infty} e^{-\bar{n}_F} \frac{\bar{n}_F^n}{n!} \qquad (6)$$

where:

n_F - the average number of photons during an interval equal to the duration of the pulse.

The video amplifier which amplifies detected laser signals should have as wide a frequency band as possible in order to be able to amplify short pulses (t_i = 20 - 50 ns). On the other side, this band should be as narrow as possible because of the noise effects in amplification of weak signals. Thus, the band width should be:

$$B = f_s - f_d \doteq f_s \geq \frac{0{,}35}{t_r} \tag{7}$$

where:

t_r = the increased time for rectangular pulse input.

In practice the time form of receiving laser pulses can be approximated by a Gauss pulse form. Thus, the band width of the video-amplifier can be calculated according to the relation:

$$B \doteq \frac{0{,}5}{t_i} \tag{8}$$

where:

t_i - duration of the input pulse at 50% of its maximum value.

The level detector at the end of the receiver causes a change of the output when the level of amplified detected signal reaches a reference value. However, because the input pulses have a Gauss form, the instant of change at the output is defined by the final pulse amplitude at the input of the level detector. This is shown in Figure 6.

The time difference t_K that appeared during the change in the output state at the level detector (because of different amplitudes of input pulses) has a significant affect on the precision of the distance determination. Thus, the error is

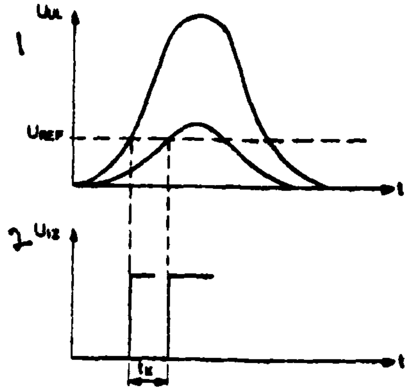

Figure 6. Input and output voltages in the level detector
1 - U_{input}; 2 - U_{output}

greater for the distant targets than for the close targets. In order to avoid the effect of amplitude of incident laser pulses on the accuracy of the measurement, video-amplifiers are designed with a time dependent amplification which is usually designated as VFP (time function amplification). The change in VFP is usually linear and thus the change in amplification from minimum to maximum appears as shown in figure 7.

It was found in practice that this effect is particularly pronounced when measuring distances of 2 - 3 km. For larger distances this effect can be neglected. Therefore, the VFP function is usually presented as a linear change for the range from 200 to 2500 m.

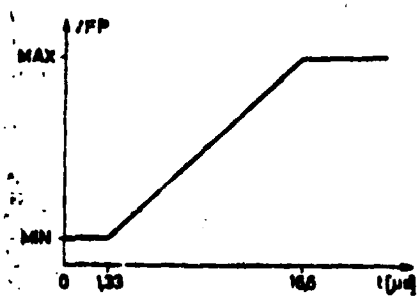

Figure 7. Typical form of a VFP function.

The level detector of the receiver system represents a subsystem which has a direct influence on the reliability of registered distances. Thus, if the threshold of the level detector were to be raised to a higher level, it would be less probable for the noise of the video-amplifier output to change the value at the level detector output, (when it is the noise and not the reflected laser signal that has changed at the level detector output, the phenomenon is referred to as a false signal). This means that the higher the threshold level the lower the probability of appearance of a false signal. However, the consequence of this is a reduction in the sensitivity of the whole receiver and probability of appearance of false signals. For the military pulse laser rangefinders the usual probability of appearance of a false signal is in the order of 10^{-3}.

The timer

As it was stated earlier these rangefinders operate on the principle of measurement of time required for the laser pulse to travel to the target and back. The relation on which the measurement of distance is based is as follows:

$$D = \frac{ct}{2} \tag{9}$$

where:

c - the speed of light
t - the time for the pulse to travel twice the distance to the target.

The modern timers are usually designed as pulse counters of time stable oscillators which generate digital pulses from the instant the laser pulse is emitted to the instant of detection (i.e. to the instant a change of state in the level detector

takes place). The accuracy of the measurement is directly related to the frequency of the oscillator and the error of the measurement is expressed as:

$$\Delta D = \pm \frac{C}{2f} \tag{10}$$

where f is the frequency of the oscillator.

In this type of timer, it is easier to use digital displays. However, the distance can also be shown on a screen of a double oscilloscope as a time delay between the emitted and received reflected laser signal.

The systems for pulse laser rangefinders

The modern pulse laser rangefinders operate mostly with lasers which have the Nd: YAG or Nd: glass as the active material. This type of emitter can be used for a range of up to 20 km and have found very broad applications, particularly in military uses.

Because the basic problem in measurements is accuracy, many original solutions have been used. Otherwise, the average accuracy can be improved by taking a number of consecutive determinations and finding an average value, i.e.,

$$\overline{D} = \frac{1}{n}\sum_{i=1}^{n} D_i \tag{11}$$

where:

n - is the number of consecutive determinations.

It has been already mentioned that the amplitude of the primary signal affects the accuracy of the range measurements. This can be avoided in two ways. First, the simplest,

is the use of VFP, which was already explained. A variation on such a solution is shown on figure 8.

At the time the emitted signal is generated the counter is placed at the starting point and starts counting the pulse oscillator counts. At that point the generator for VFP function starts to operate - and to control amplification of the video - amplifier. When the pulse reflected from the target is received, the counter stops and the indicator displays the counter content i.e. the distance to the target. The other variation is somewhat more complicated and is based on constant comparison of amplitude of the receiving signal with a reference value. In case of deviations from the amplitude value, a correction of laser radiation power and video-amplifier is carried out automatically. The principle is illustrated by a block schematic diagram in figure 9.

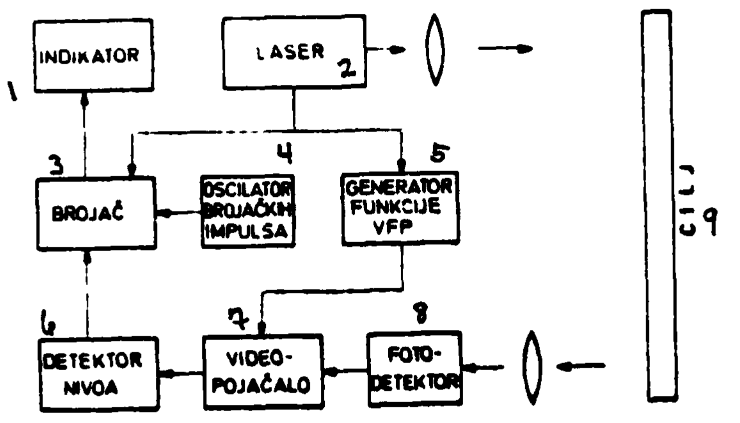

Figure 8. Pulse laser rangefinder with a VFP function generator
Key: 1 - indicator; 2 - laser; 3 - counter; 4 - oscillator of counted pulses; 5 - VFP function generator; 6 - level detector; 7 - video amplifier; 8 - photodetector; 9 - target.

In this system the laser operates as an emitter of pulses of frequency f_1, which is determined by the impulse generator.

The f_i frequency must satisfy the relation:

$$f_i < \frac{C}{2 D_{max}} \tag{12}$$

In this case there will be no overlap of the reflected pulse with the instant of formation of a new emitting pulse. When at the output of the video-amplifier the amplitude of the received signal differs from the one required, the regulation system affects the laser excitement mechanism which changes the emission energy. The photodetector parameters change also, until the detected pulse reaches the required amplitude.

The range determination is constantly connected with receiving of pulses reflected from objects and articles which are within the field of view. Particularly undesirable is registering targets which are closer than the desired targets. This is avoided by application of a method of the, so called, selected signals. This principle is illustrated by a block diagram in figure 10.

In this system the operator uses a manual signal selector to determine the, so-called, masked distance. Within this distance, target distances can not be read on the indicator. This means that in practice only those target distances that are beyond the masked range can be read.

The modern military pulse laser rangefinders, of medium category, can select targets, measure distances of multiple targets and indicate the existence of targets other than those that are being measured. A schematic principle of such a rangefinder is shown in figure 11, with the assumption that this rangefinder is capable of determining distances of two targets and indicate existence of other targets either closer or farther than those being measured.

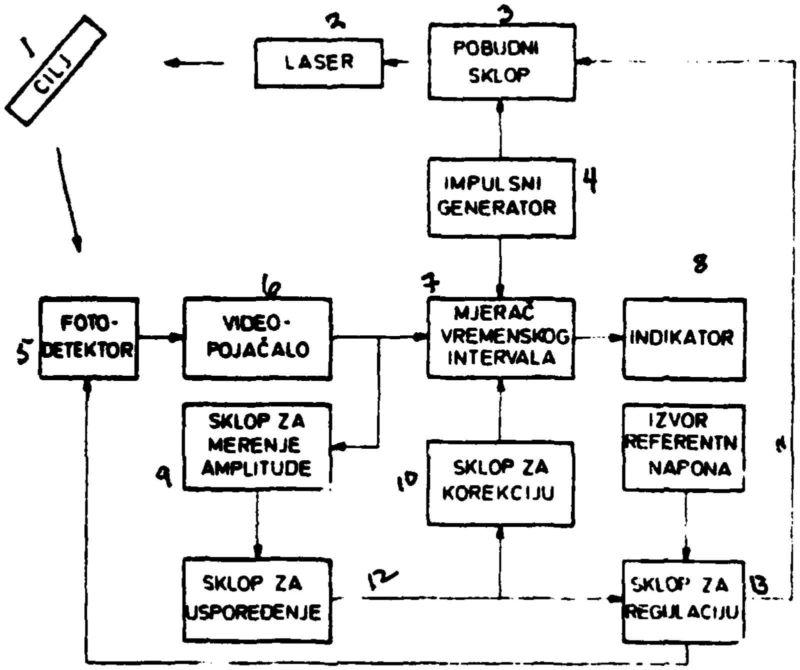

Figure 9. Pulse laser rangefinder with automatic regulation of amplification and laser emitting power.

Key: 1 - target; 2 - laser; 3 - excitement system; 4 - pulse generator; 5 - photodetector; 6 video amplifier - 7 - interval timer; 8 - indicator; 9 - amplitude measurement system; 10 system for corrections; 11 - reference voltage source; 12 - comparison system; 13 - regulation system.

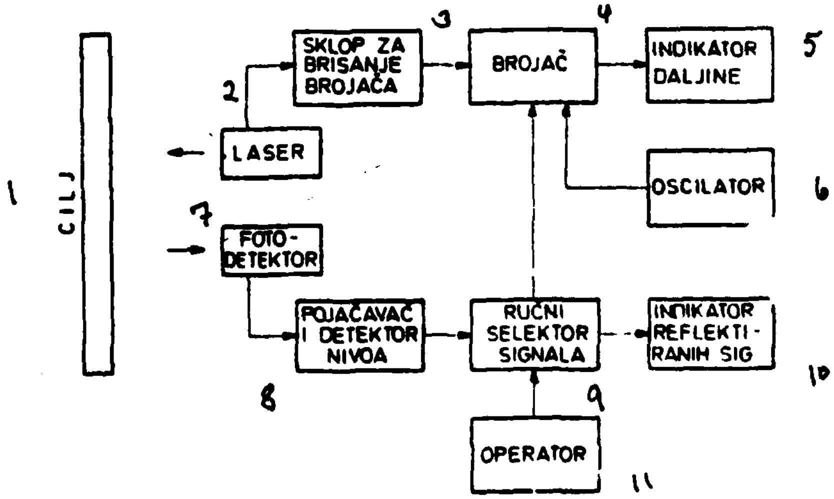

Figure 10. Pulse laser rangefinder with signal selector.
Key: 1 - target; 2 - laser; 3 - counter eraser system; 4 - counter; 5 - distance indicator; 6 - oscillator; 7 - photodetector; 8 - amplifier and level detector; 9 - manual signal selector; 10 - indicator of reflected signals; 11 - operator.

Using manual selector, the operator selects two targets whose distance could be read on target pointers 1 and 2. If there are other targets in the field either closer or farther than the targets being measured their presence will be indicated on indicators 1 and 2.

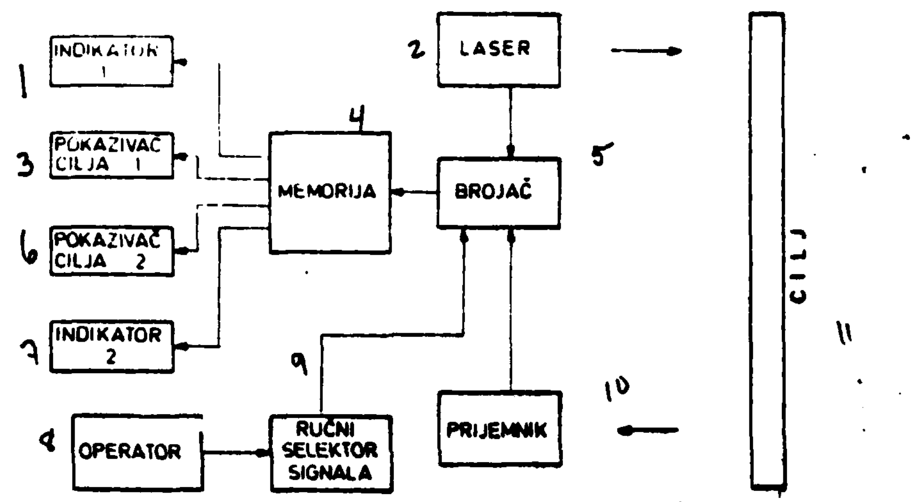

Figure 11. Schematic block diagram of the principle of a modern pulse laser rangefinder.

Key: 1- indicator; 2 - laser; 3 - target pointer; 4 - memory; 5 - counter; 6 0 target pointer 2; 7 - indicator; 8 - operator; 9 - manual signal selector; 10 receiver; 11 - target.

This simultaneous determination of a number of targets is enabled by a relatively large divergence of the laser beam, and at larger distances the beam cross-section has a sufficiently large area to encompass a number of targets. More expensive and more precise laser rangefinders have a very low divergence so that the target pointer shows only the range of the target at which it is being aimed through the telescope.

<u>Conclusion</u>:

This short review of pulse laser rangefinder systems leads

to the conclusion that this finder represents a complex instrument and that its application procedure requires finding compromises between contradictory requirements. However, in practice this rangefinder is very mobile and simple to operate and can, in addition, be set in advance for the desired accuracy. In this respect, the application use of the rangefinder must always be considered, because excessive accuracy in certain situations can cause unnecessary cost and complications of the instrument. Therefore, a variety of models have been designed with special characteristics, modified for special applications.

From the viewpoint of modern developments and application of technology for military purposes one can not imagine a modern army that is not equipped with this type of rangefinder.

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